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On hydrogen and hydrogen energy strategies I: current status and needs

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Abstract

This article deals with hydrogen energy as a clean energy carrier, discusses the key role of hydrogen energy technologies and systems, and compares hydrogen with other energy forms. Energy strategies that incorporate hydrogen are considered, and the importance of hydrogen energy in achieving a sustainable energy system is discussed. Exergetic, environmental, sustainability and other perspectives are considered.

Keywords: Energy; Exergy; Hydrogen; Renewable energy; Sustainability

Contents

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1. Introduction

Energy is an essential commodity for increasing productivity in both agriculture and industry. An increase in the energy consumption of a country provides a positive impact on the economic as well as social development of the country. Moreover, the supply and utilization of low-priced and clean fuel is particularly significant for global stability and peace since energy plays a vital role in industrial and technological developments around the world [1]. Critical energy issues in the 21st century will likely include energy security for up to 12 billion people, the expected global population by the middle of the 21st century, and global warming, mainly caused by CO_2 emissions generated from the combustion of fossil fuels [2]. In the 1990s, the world struggled with important problems such as shortages of fossil fuels and pollution. In addition, the energy requirement of the world has been increasing due to increasing world population, technological development, and increased living standards. These factors have led to world population transition, migration, hunger, environmental (especially air and water pollution) problems, deteriorating health and disease, terrorism, energy and natural resources concerns, and wars. These effects can increase troubles in the world.

As a consequence, investigations of alternative energy strategies have recently become important, particularly for future world stability. The most important property of alternative energy sources is their environmental compatibility. In line with this characteristic, hydrogen likely will become one of the most attractive energy carriers in the near future. Much research, including experimental and theoretical studies, have recently been carried out on hydrogen energy. However, it is necessary to understand the broader aspects of hydrogen energy.

Many significant recent studies have demonstrated the importance of hydrogen energy. Some focus on the contributions that hydrogen can make to sustainable development [3–7]. Others focus on hydrogen's potential contributions to resolving environmental issues [1,8–10], or review the current and past status of hydrogen energy [11–14]. The future prospects for hydrogen energy, especially the concept of a hydrogen economy, are the focal point of many articles [15–20].

These studies indicate that the role of hydrogen energy will become increasingly important, with many researchers describing how world energy systems may

undergo a transition to an era in which the main energy carriers are hydrogen and electricity [21].

Unlike the above studies, this article focuses on hydrogen energy strategies, and discusses the key role of hydrogen energy in this century and beyond. Also, this article presents the reasons why hydrogen is required, alternative fuel properties, and hydrogen's relation to energy sources and utilization fields. Also investigated and discussed is the role hydrogen can play in reducing the global environmental effects of fossil fuels, halting energy-related world conflicts, and ensuring world stability and peace in this century and beyond. The primary objective of this article is to discuss the key role of hydrogen, and hydrogen energy technologies and strategies, in achieving a more environment friendly and a more sustainable society.

2. Advantages and disadvantages of hydrogen energy

Some important advantages of hydrogen follow:

- Hydrogen is a non-toxic, clean energy carrier that has a high specific energy on a mass basis (e.g., the energy content of 9.5 kg of hydrogen is equivalent to that of 25 kg of gasoline [22]).
- Many production processes for hydrogen exist [23], including processes where some of the hydrogen is contributed by fossil fuels (e.g., steam reforming of natural gas or other light hydrocarbons, gasification of coal and other heavy hydrocarbons), electrolysis of water, direct and indirect thermochemical decomposition, and processes driven directly by sunlight.
- Hydrogen can be safely transported in pipelines.
- Hydrogen can be used advantageously as a chemical feedstock in the petrochemical, food, microelectronics, ferrous and non-ferrous metal, chemical and polymer synthesis, and metallurgical process industries, and as an energy carrier in clean sustainable energy systems.
- When combusted, hydrogen produces non-toxic exhaust emissions, except at some equivalence ratios (where its high flame temperature can result in significant NO_x levels in the exhaust products) [24,25].
- Hydrogen can be generated from various energy sources, including most renewable ones.
- Compared to electricity, hydrogen can be stored over relatively long periods of time.
- Hydrogen can be utilized in all parts of the economy (e.g., as an automobile fuel and to generate electricity via fuel cells).

Some disadvantages of hydrogen follow:

- When mixed with air, hydrogen can burn in lower concentrations and this can cause safety concerns.
- Storage of hydrogen in liquid form is difficult, as very low temperatures are required to liquefy hydrogen.

3. World problems and hydrogen energy

Effects of the utilization of fossil fuels, such as global climate change, world energy conflicts and energy source shortages, have increasingly threatened world stability. These negative effects are observed locally, regionally and globally. If increasing use is made of fossil fuels, significant global problems will probably increasingly occur. These are listed in Fig. 1 and discussed in detail below.

3.1. Decrease in fossil fuel reserves due to world population growth, technological developments, and increasing energy demand

In the past, fossil energy sources could be used to solve world energy problems. However, fossil fuels cannot continue indefinitely as the principal energy sources due to the rapid increase of world energy demand and energy consumption. The utilization distribution of fossil fuel types has changed significantly over the last 80 years. In 1925, 80% of the required energy was supplied from coal while in the past few decades, 45% came from petroleum, 25% from natural gas and 30% from coal. Due to world population growth and the advance of technologies that depend on fossil fuels, reserves of fossil fuel eventually will not be able to meet energy demand. Energy experts point out that reserves are less than 40 years for petroleum, 60 years for natural gas and 250 years for coal [2,22]. Fossil fuel costs are thus likely to increase in the near future. This will allow renewable energy sources such as solar, wind, hydrogen, etc., to be utilized. As an example, observed and predicted quantities of world energy production and consumption from 1971 to 2040 are displayed in Fig. 2. Based on the past data from Refs. [26,27], a correlation between world energy production and consumption is observed, and used to obtain the future projections as shown in Fig. 2:

$$\mathrm{WEP} = 144.610 \times Y - 279\,195 \tag{1}$$

and

$$\mathrm{WEC} = 133.066 \times Y - 256\,910 \tag{2}$$

where WEP is the world energy production (Mtoe), WEC is the world energy consumption (Mtoe) and Y is the time (years).

According to Fig. 2, quantities of world energy production and consumption are expected to reach 15 810.74 Mtoe and 14 544.02 Mtoe, respectively, by the year 2040. World population is now over 6 billion, double that of 40 years ago, and it is likely to double again by the middle of the 21st century. The world's population is expected to rise to about 7 billion by 2010. Even if birth rates fall so that the world population becomes stable by 2040, the population would still be about 10 billion. The data we have presented in Fig. 2 are expected to cover current energy needs provided the population remains constant. Since the population is expected to increase drastically, conventional energy resource shortages are likely, due to insuf-

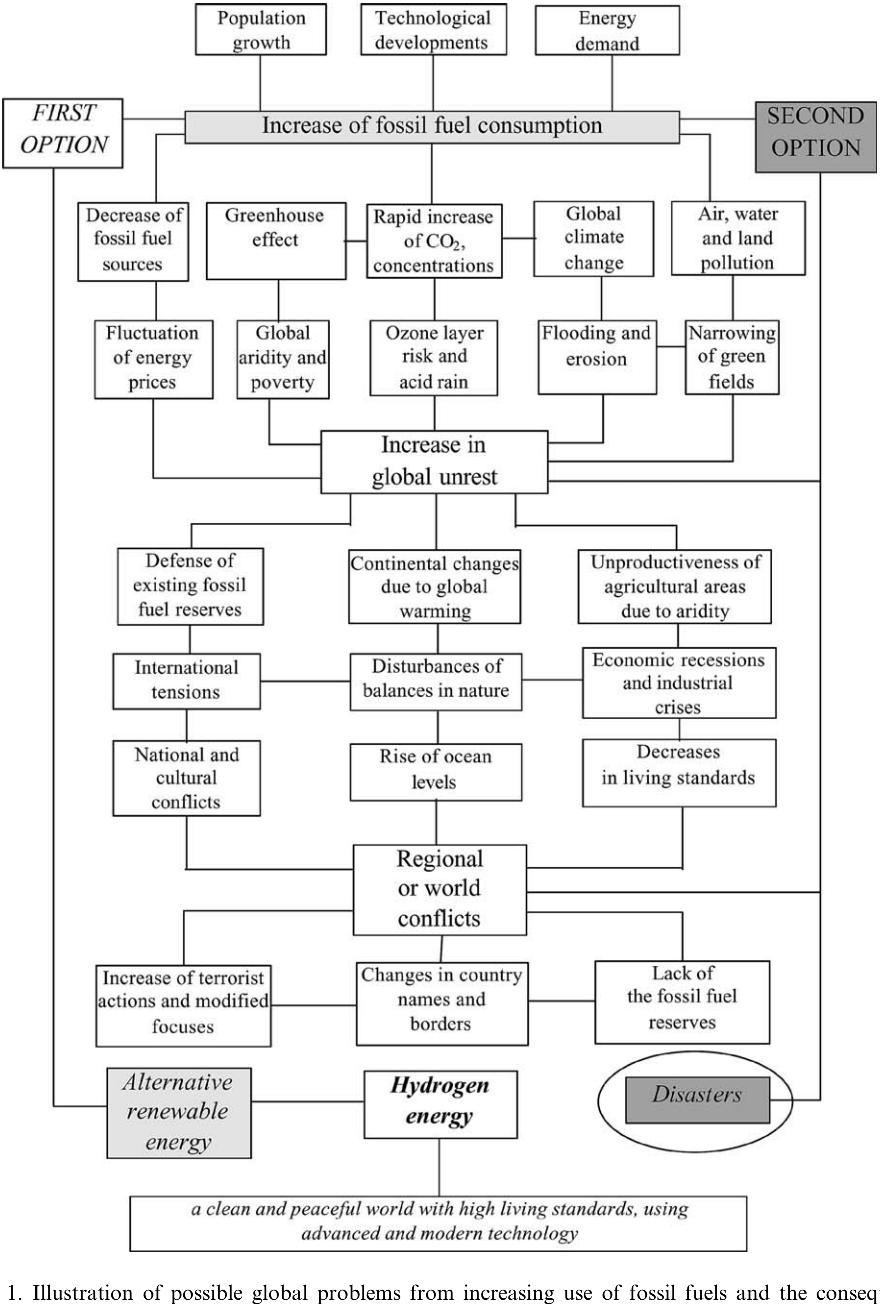

Fig. 1. Illustration of possible global problems from increasing use of fossil fuels and the consequent need for hydrogen energy systems. The key drivers are shown at the top. The first option (shown on the left) follows a path of increasing use of renewable and sustainable energy, while the second option (right) allows for increasing use of fossil fuels and the problems related to that path.

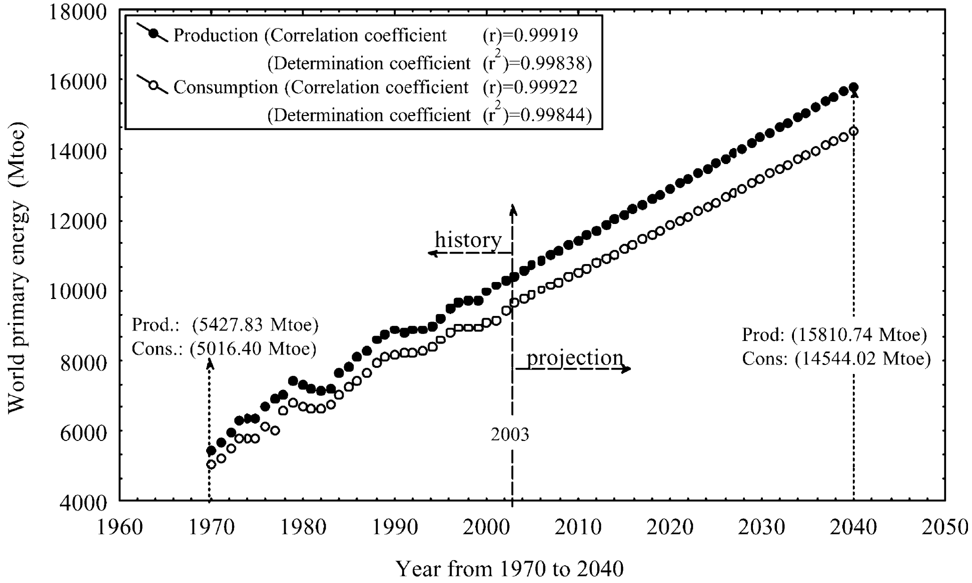

Fig. 2. Variation of world energy production and consumption using observed data [26,27] and future projections.

ficient fossil fuel resource supplies. In the near future, therefore, renewable energy will become increasingly important to compensate for shortages of conventional resources. Hydrogen energy will likely be important in facilitating increased use of renewables.

3.2. Global climate change due to the increase of carbon dioxide concentration in the atmosphere

The main environmental effects of fossil fuels are realized during their utilization. Tar, dust and harmful gases such as CO_x, SO_x, NO_x, etc. that cause air pollution are discharged to the atmosphere. Fossil fuels are used for many applications, including industry, residential, commercial and other sectors. Increasing fossil fuel utilization in transportation vehicles such as automobiles, ships, aircraft and spacecraft has led to increasing pollution. Gas, particulate matter and dust clouds in the atmosphere absorb a significant portion of the solar radiation directed at the Earth, and cause a decrease in the oxygen available for the living things. The threat of global warming has been attributed to fossil fuels. For example, the CO_2 emission per unit of fossil fuel energy (in GJ) depends on fossil fuel type, and is around 85.5 kg CO_2 for coal, 69.4 kg CO_2 for petroleum and 52 kg CO_2 for natural gas. It is expected that emissions of CO_2 will reach 8.2–10.0 gigatons around 2020 [2,22]. Global climate change due to CO_2 emissions is possibly the most important environmental problem that human beings face. The average annual temperature of Earth has increased 0.7 °C since 1860. If the utilization of fossil fuels continues

at today's pace, the world's annual average temperature is predicted by some to increase 1.25 °C by 2025, 2.2 °C by 2050, 3.5 °C by 2075 and 5.4 °C by 2100, due to the rise in atmospheric CO_2 concentration [2,22]. If the utilization of fossil fuels reaches to 1000 EJ (1 exajoule = 10^9 GJ = 22.7×10^6 TEP (ton equivalent petrol)) in 2050, world average temperature will likely rise between 3 and 5 °C. This increase in temperature is sufficiently high to affect significantly life across the world. A 1 °C rise in temperature may change climates in many areas of the north and south hemisphere. An annual average world temperature increase of almost 5 °C would likely raise the levels of seas and oceans more than 1 m due to ice melting in the poles, and cause agricultural poverty, erosion and floods [2]. Thus, the negative effects from the usage of fossil fuels need to be appropriately averted, and hydrogen presents one potential solution.

3.3. Conflicts and wars due to fluctuations of energy prices, economic recessions, decrease of living standards and increase of unrest among countries

The decrease of available fossil fuel reserves and increased fuel costs since the mid- to late-1900s has led to variations in lifestyles and standards of life. These effects have in some regions decreased living standards of entire societies. Countries that need more energy resources have been purchasing cheaper energy sources. Countries that look after the future welfare of their societies have received the attention of countries that possess fossil fuel supplies, posing the potential for world conflict. Problems are often attributed to decreases of fossil fuel energy reserves.

Sustainable energy sources that are abundantly available can

- reduce or stop conflicts among countries regarding energy reserves,
- facilitate or necessitate the development of new technologies,
- reduce air, water and land pollution and the loss of forests,
- reduce energy-related illnesses and deaths.

Accordingly, the transition to a hydrogen economy should be encouraged, and developed countries, in particular, should increase investments in hydrogen energy.

4. Historical developments relating to hydrogen

Hydrogen comes from the Greek words "hydro" and "genes" meaning "water" and "generator". Hydrogen, the first element in the periodic table, is the least complex and most plentiful element in the universe [28–30]. Hydrogen is a key part of water, which covers over 60% of the planet's surface. Hydrogen appears in different forms in plants, animals, humans, fossil fuels, and other chemical compounds [31]. Many researchers have contributed to the historical development of hydrogen, as shown in Table 1.

In the 20th century, hydrogen was extensively used in the manufacture of ammonia, methanol, gasoline and heating oil, as well as in such commodities as

Table 1
Historical developments related to hydrogen

Time period	Scientist	Contribution
16th Century	Paracelsus	Understanding of properties of hydrogen, including its flammability
16th Century	Van Helmot	Described hydrogen as a special kind of gas
17th Century	Robert Boyle	Produced hydrogen gas while experimenting with iron and acids
18th Century	Henry Cavendish	First recognized hydrogen as a distinct element
18th Century	Lavoisier	Hydrogen named
19th Century	Anonymous	Development of idea that hydrogen could be an energy carrier that facilitates use of renewable energy sources
19th Century	Carl Bosh	Hydrogen used in production of fertilizer
20th Century	Kordesch	Hydrogen used in vehicles
20th Century	T.N. Veziroglu	Organization of symposia on hydrogen energy, leading to expanded hydrogen energy study and utilization over the world

fertilizers, glass, refined metals, vitamins, cosmetics, semi-conductor circuits, lubricants, cleaners, margarine and rocket fuel. After 1974, many studies were conducted to investigate the uses for hydrogen energy and facilitate its penetration as an energy carrier. Subsequently, many industries worldwide began developing and producing hydrogen, hydrogen-powered vehicles, hydrogen fuel cells, and other hydrogen-based technologies [32].

5. Why hydrogen as an energy carrier?

Hydrogen is expected to play an important role in future energy scenarios. The foremost factor that will determine the specific role of hydrogen will likely be energy demand. Hydrogen is expected in the future to replace to some degree fossil fuels and to become the preferred portable energy carrier for vehicles.

Currently 500 billion cu m of hydrogen, equating to about 6.5 EJ of energy, are produced annually worldwide. Approximately, 99% is produced from fossil fuels, mainly by steam reforming of natural gas [33]. It is possible to produce hydrogen using other production techniques and different energy sources. Renewable energy sources such as hydraulic, solar, wind, geothermal, wave and solid waste energy can be used to generate hydrogen from hydrocarbons and/or water. For instance, 108.7 kg of hydrogen can be produced from $1 m^3$ of water by electrolysis using electricity, and the energy of this amount of hydrogen is equivalent to that of 422 l of gasoline [2,22,31,32]. The electricity for hydrogen production can come from fossil or renewable energy sources. Considering the energy density on a mass basis (which is 141.9 MJ/kg for liquid (LH_2) or gaseous (gH_2)), the utilization efficiency factor ($\beta_\mu = \eta_f/\eta_h = 1$) [32], utilization safety (which is high for hydrogen), the motivity factor (=1 for LH_2 and gH_2), pollution and environmental effects (which can be low for hydrogen, depending on the energy source used to produce it, especially since CO_2 is not a necessary waste) of hydrogen fuel [32], hydrogen energy has many attractive features. Fig. 3 presents the importance, production

techniques and application areas for hydrogen. The application areas are drawn from the literature [2,11,20,21,32,34,35], and commonly appear in the developed countries, such as the U.S., Canada, Japan and Germany, that spend much money to advance technological applications.

Hydrogen's attributes as an energy carrier relate to energy demand, production techniques and application fields, and include the following: clean, not harmful to the environment or life, renewable, securely storable and transportable, broadly utilizable in various applications, producible by different techniques and from various sources, and economically usable. The attributes and properties of hydrogen, and a comparison of hydrogen with other fuels, are presented in Tables 2 and 3.

The above features of hydrogen suggest that it will be particularly advantageous as a transportation fuel because of its versatility, utilization efficiency factor and safety [32]. The only waste from hydrogen oxidation is water, so only the engine lubricants from a hydrogen-fueled vehicle cause any pollutants.

6. A hydrogen economy

The transition to a hydrogen-based energy economy, where the main chemical energy carrier is hydrogen and the main non-chemical energy form is electricity, is being made gradually, and is likely to continue to the middle or end of the 21st century.

Current world hydrogen production is approximately 50 million tons/year (45 billion kg/year), which represents 2% of world energy demand [36]. However, current total annual worldwide hydrogen consumption is in the range of 400–500 billion N m^3. Of this quantity, approximately 97% is represented by captive or internal production and only about 3% is provided from merchant sources [37].

To expand the role of hydrogen in the near term, several approaches are being proposed. One is to use hydrogen for transportation by mixing it with natural gas as a fuel for internal combustion engines; this would increase engine performance and decrease pollution. Another approach involves producing hydrogen at central locations and distributing it to refueling stations. There, it will be pumped into vehicles for use in fuel cell and other power plants. Hydrogen-powered fuel cell vehicles produce no emissions other than water vapor [38], and are an important element in California's legislative mandate for the introduction of zero-emission vehicles.

A hydrogen economy will likely be introduced over a long time period and involve several phases:

- In the near term, hydrogen will be produced primarily by advanced steam reforming of natural gas, either at central or distributed facilities. This process presents an opportunity to decrease the amount of carbon dioxide released to the atmosphere, since a byproduct of steam reforming is a high-purity carbon dioxide that can be collected and used, or sequestered in many ways, such as in coal seams, depleted natural gas fields, or saline aquifers.

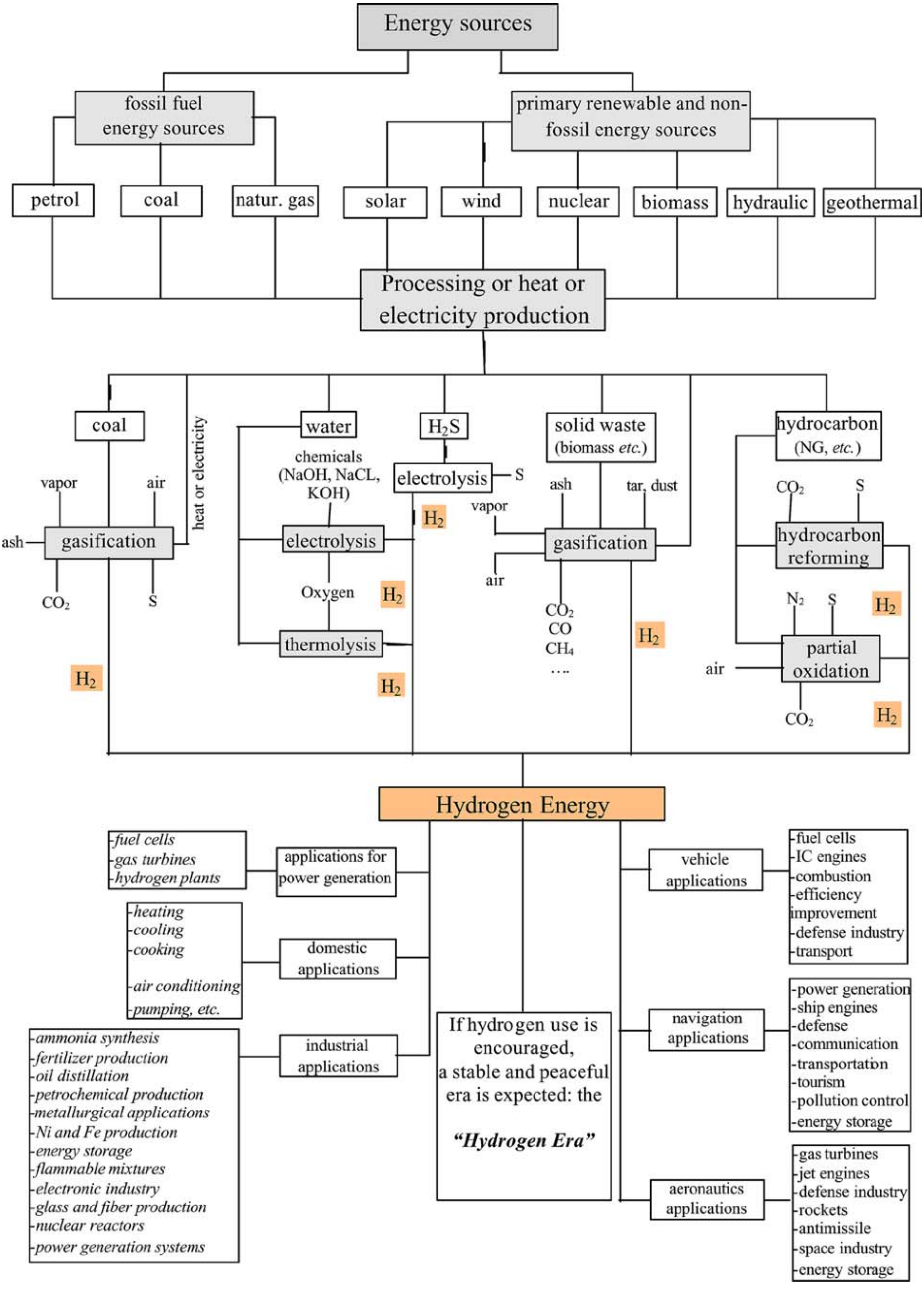

Fig. 3. Relationship of production techniques and types of utilization of hydrogen.

Table 2
Properties of hydrogen as a fuel

Property	Unit	Value
Density[a]	kg/m^3	0.0838
HHV and LHV	MJ/kg (liquid)	141.9–119.90
HHV and LHV	MJ/m^3 (volumetric)	11.89–10.05
Boiling point	K	20.41
Freezing point	K	13.97
Density (liquid)	kg/m^3	70.8
Diffusion coefficient in air[a]	cm^2/s	0.61
Specific heat at constant pressure	kJ/kg K	14.89
Ignition limits in air	% (volume)	4–75
Ignition energy in air	millijoule	0.02
Ignition temperature	K	585
Flame temperature in air	K	2318
Explosion energy	kJ/g TNT	58.823
Flame emissivity	%	17–25
Stoichiometric mixture in air	%	29.53
Stoichiometric air/fuel	kg/kg	34.3/1
Flame velocity	cm/s	2.75
Motivity factor	–	1.00

Sources: Refs. [2,27,30,32].
[a]At normal temperature and pressure.

- In the intermediate term, restructuring of the electric utility industry will present opportunities for distributed generation, where hydrogen-powered fuel cells will provide on-site generation of electricity. In addition to electricity, these fuel cells will also produce thermal energy for hot water, space heating, and industrial pro-

Table 3
Comparison of key properties for hydrogen and other fuels

Fuel type	Energy per unit mass (J/kg)	Energy per unit volume (J/m^3)	Motivity factor	Specific carbon emission (kg C/kg fuel)
Liquid hydrogen	141.90	10.10	1.00	0.00
Gaseous hydrogen	141.90	0.013	1.00	0.00
Fuel oil	45.50	38.65	0.78	0.84
Gasoline	47.40	34.85	0.76	0.86
Jet fuel	46.50	35.30	0.75	–
LPG	48.80	24.40	0.62	–
LNG	50.00	23.00	0.61	–
Methanol	22.30	18.10	0.23	0.50
Ethanol	29.90	23.60	0.37	0.50
Bio diesel	37.00	33.00	–	0.50
Natural gas	50.00	0.04	0.75	0.46
Charcoal	30.00	–	–	0.50

Sources: Refs. [2,30,32,34].

cesses. During this phase, hydrogen will be increasingly produced from coal and from the pyrolysis or gasification of biomass. Biomass for hydrogen production will come from dedicated crops, agricultural residues, or municipal solid wastes. Dedicated crops will be particularly valuable for offsetting carbon dioxide emissions because biomass crops re-grown specifically for energy recycle carbon dioxide from the atmosphere, resulting in no net carbon dioxide emissions. In the intermediate term, an increasing number of hydrogen-fueled zero-emission vehicles will also be on the road, due to improvements in onboard storage and other technologies. This occurrence, in turn, will provide impetus for building a hydrogen infrastructure along dedicated transportation corridors or clusters of use.
- In the long term, strong hydrogen markets and a growing hydrogen infrastructure will create opportunities for renewable hydrogen systems. Intermittent energy technologies such as wind turbines or photovoltaics, for example, will power electrolysis to produce hydrogen for fuel cells. The fuel cells will use the hydrogen to provide electricity during higher demand periods or to supplement the intermittent energy sources. This era will likely also witness the emergence and growth of advanced technologies that produce hydrogen from water and sunlight and that store hydrogen in high-energy-density systems. Market penetration of advanced technologies to produce, store and use hydrogen will mark the establishment of the hydrogen energy economy.

Jones [39] cites several uncertainties regarding a hydrogen economy [39]:

- The "hydrogen economy" is an end state based on hydrogen produced from renewable energy such as solar or wind. But, it is not yet economic to produce hydrogen in this way.
- Hydrogen-powered fuel cells promise to provide clean and efficient energy for future vehicles and stationary power generation, but that is only achievable if the hydrogen is produced cleanly.
- A long transition to hydrogen from hydrocarbons is likely.
- Cost and technical hurdles must be overcome to allow mass adoption of fuel cells and other hydrogen technologies.

Despite these issues, there is increased momentum for a hydrogen economy due to global environmental problems, energy security and supply issues, and technological innovations, as shown schematically in Fig. 4.

7. Exergetic and sustainability aspects of hydrogen

The impact of energy resource utilization on the environment and the achievement of increased resource-utilization efficiency are best addressed by considering exergy. The exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change and provides the basis for an effective measure of the potential of a substance or energy form to impact the environment. In practice, a thorough understanding of exergy, as well as the insights it can provide

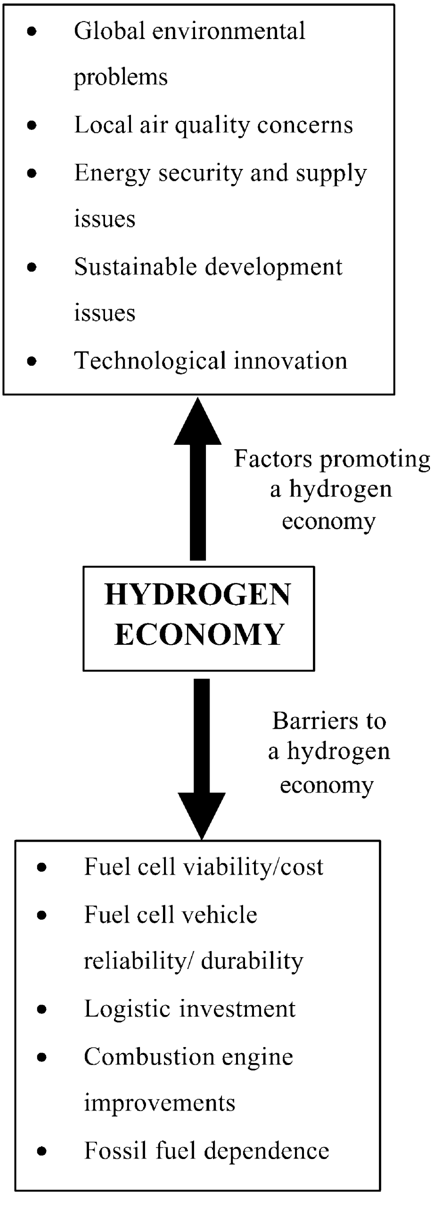

Fig. 4. Factors supporting and opposing the development of a hydrogen economy.

into the efficiency, environmental impact and sustainability of energy systems, are helpful if not required for the engineer or scientist working in the area of energy systems and the environment [40].

One of the authors has performed extensive exergy-based investigations into hydrogen production and utilization processes (e.g., fuel cells for electricity and for cogeneration) [23,38]. The additional insights into processes that are provided using exergy methods provide several benefits:

- a better understanding is provided of the performance of the processes, and especially of their efficiencies and thermodynamic losses,
- the margins for improvement via specific measures to improve efficiency are more accurately and meaningfully revealed, and
- recommendations can be rationally made regarding specific measures for improving processes and/or better integrating them into larger processes (even regional or national energy systems).

During the past decade, the need to understand the linkages between exergy and energy, and environmental impact, has become increasingly significant [10]. Exergy, because it is a measure of the departure of the state of a system or substance from the state of the environment, allows the potential environmental harm due to the emission of a substance to be estimated, and this application of exergy may in the future allow the environmental harm due to an emission to be predicted without emitting the substance and observing the effects.

For hydrogen technologies and systems, applications of exergy methods can have numerous broad and comprehensive benefits:

- a better knowledge of the efficiencies and losses for the technologies and systems, and how they behave and perform,
- a clearer appreciation of the environmental impacts of hydrogen energy systems, as well as the mitigation of environmental that they can facilitate, and
- better identification of the ways hydrogen systems can contribute to sustainable development.

Hydrogen energy systems have the potential to provide the foundation for sustainable energy systems [41]. Production of hydrogen can be carried out sustainably since hydrogen can be produced from renewable and sustainable energy sources. Energy services can be provided sustainably through hydrogen since it can be used to drive the industry, transportation, commercial, institutional, residential and other sectors of the economy with little or no emissions.

Winter [42] offers insights into the development of hydrogen-based decarbonized, hydrogenated and dematerialized energy markets. Energy technologies now provide more clean energy services at the back end of the energy conversion chain from less environmentally harmful and climate change risking carbonaceous energy raw material at its front end. Energy technologies allow better exergy use by the nation's energy system.

The national energy efficiency of an industrial nation (e.g., in Germany) is about 30%. Thus, 3 kW h of primary energy raw materials must be introduced into the national economy at the front end of the energy conversion chain in order to pro-

vide 1 kW h of energy services at its back end. The energy efficiency of the world is even lower, about 10% [42]). However, energy efficiencies are only one kind of optic; a much more important different optic is provided by exergy efficiency, which is a measure how much of the introduced energy raw material is converted into something enabling us to perform technical work. The exergy efficiency of the economy of Germany is about 15%, and that of the world only a few percent. The most inefficient exergetic links of the national energy conversion chain are at its back end, where end-use energy is converted to useful energy and provides energy services. For instance, the central heating system of a residential household is highly efficient energetically, but of a very low efficiency based on exergy. Similarly for automobile transport, only 20–25% of the energy content in the fuel tank is converted to the longitudinal motion of the vehicle.

Hydrogen from coal can exergetically improve the system, in both of the above cases. Hydrogen from coal can drive household fuel cells at 35–40% efficiency, and yields electricity, which is pure exergy and can be converted to any other form of energy. The exhaust heat still contains sufficient exergy to heat the radiators of the dwelling. Similarly, hydrogen in the tank of an automobile can drive a fuel cell, which generates electricity efficiently to operate the electric drive train of the vehicle. Since the energy sector's residences and transport devices consume about two-thirds of many nation's end-use energy demand, the potential importance of coal-derived hydrogen is evident.

Historically, the switch from coal to oil and further to natural gas in the last 120 years has decarbonized energy-specific carbon-containing energy by some 35% [43]. It is to be expected that the further switch to increased efficiency, to carbon-free renewable energies, and finally to hydrogen, will perpetuate the trend to less carbon, more hydrogen and, consequently, to dematerialized energy.

8. Conclusions

This article presents the key role of hydrogen as a clean energy carrier and discusses hydrogen technologies and strategies from exergetic, environmental, sustainability and other perspectives. Investigating the needs for hydrogen energy and systems allow future strategies incorporating hydrogen energy to be considered in a logical manner. The impact of hydrogen energy on world unrest and stability is considered in the second part of this paper.

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